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Notch Fatigue Strength of a PM Disk Superalloy

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Introduction

New powder metallurgy (PM) disk superalloys, such as ME3 (ref. 1), LSHR (ref. 2), and Alloy 10 (ref. 3), have been developed in recent years which enable rim temperatures in turbine disk applications to approach 1300 °F. Before these alloys can be utilized at 1300 °F their long term durability must be ensured. One of the key requirements for disk rims is notch fatigue strength. This issue is extremely important and is a direct result of the blade attachment geometry employed at the disk rim. Further, the imposition of a dwell at maximum load, associated with take off and landing, can also compromise notch fatigue strength (ref. 1). For these reasons a study has been undertaken to assess the notch dwell fatigue strength of a modern PM disk alloy through spin pit evaluation of a prototypical disk. The first element of this program involves screening potential heat treatments with respect to notch fatigue strength at 1300 °F utilizing a conventional notch fatigue specimen with a stress concentration factor (K_t) of 2 and a 90 sec dwell at peak load. The results of this effort are reported in this paper including the downselect of an optimal heat treatment, from a notch fatigue standpoint.

Material and Procedures

The material selected for this program was LSHR, a 3rd generation PM superalloy, strengthened by about 60 percent gamma prime phase. The composition of LSHR is presented in table I. LSHR powder was produced using argon gas atomization and was consolidated via the hot isostatic pressing and extrude route to produce a 3.5 in. diameter billet. Mults cut from the billet were isothermally forged to produce pancake forgings about 6 in. in diameter and 1.5 in. in height. Six commercially viable heat treatments, presented in table II, were evaluated in this program. Four produced fine grain microstructures, about ASTM 11, utilizing a subsolvus solution step and two produced coarse grain microstructures, about ASTM 7, utilizing a supersolvus solution step. The subsolvus solution step was followed by an oil quench or a gas fan quench while the supersolvus solution step was followed by a gas fan quench. After the solution and quench, the forgings were given a single step age, 1425 °F/8 hr, or a two step age, 1570 °F/4 hr, and 1425 °F/8 hr. Each heat treat option was designed to produce a different mix of tensile, creep, and crack growth properties.

Standard mechanical tests were run at 1300 °F to verify the tensile, creep, and crack growth properties of each heat treat option. Creep tests were run at 115 ksi using a combo test bar presented in figure 1, while crack growth tests were run with a 90 sec dwell at peak load using a K_b specimen described in reference 4. Stress relaxation tests were also run employing tensile specimens which were loaded to and held at 1 percent strain for a minimum of 100 hr.

The notch dwell fatigue tests were run using the geometry depicted in figure 2. A low stress ground, longitudinal polish was employed to cut the notch and therefore minimize specimen to specimen variation associated with surface finish at the critical location. As previously stated, the specimen provided a K_t of 2. A peak, net section stress of 115 ksi was applied for 90 sec in each cycle as shown in figure 3. The selection of stress was aggressive but reasonable for a disk rim application. As these tests are quite lengthy, the initial screening matrix called for testing up to six specimens from each heat treat lot to failure or a 10,000 cycle runout condition, approximating the life requirement for turbine disks. A subsequent study will be undertaken to obtain fatigue lives of those specimens which exceed 10,000 cycles in duration.

Results and Discussion

The microstructure for each heat treat option is presented in figure 4. The features observed in these microstructures are in line with expectations. In addition to the grain size difference between the subsolvus and supersolvus heat treatments, the subsolvus microstructures contain micron size primary gamma prime. Also note, the oil quench produces a finer secondary gamma prime structure compared with the gas fan quench.

Tensile and creep test results are presented in tables III and IV, respectively. As with microstructure, the observed trends are in line with expectations. With respect to the tensile data, it is interesting to note the elongation for all heat treatments hover about 10 percent with the exception of H2 which approaches 20 percent. However, H2 also exhibits the lowest yield strength. Creep times to 0.2 percent and rupture lives of the combo bars are tabulated in table IV. All of the combo bars listed in table IV failed in the smooth section. The ranking of creep lives was in line with previous results for this alloy (ref. 2). Most notably, the two step aging sequence is seen to diminish creep capability, as gamma prime precipitate size coarsens. Stress relaxation data for the six heat treat options is presented in figure 5. As one might expect, the ranking for the stress relaxation data approximates the ranking for the creep data, i.e., microstructures prone to lower creep rates also maintained higher stress levels at a given time in the relaxation tests.

Dwell crack growth rates of the six heat treats are presented in figure 6. As with tensile and creep data, the ranking of crack growth rates was in line with previous data on LSHR. The six heat treats produced differences of over one order of magnitude in crack growth rates at 1300 °F, with the H2 microstructure being significantly better than all others.

Notch dwell fatigue testing of the first twelve specimens, two from each heat treat, produced very interesting results. Three of twelve failed in less than 1,000 cycles while all others reached the 10,000 cycle runout condition. Based on these results, the remaining 24 tests were run to a 2,000 cycle runout criteria to accelerate data acquisition and enhance statistics on the low life failure phenomenon, i.e., lives less than a 1,000 cycles. The results of all 36 tests are summarized in table V and figure 7. As seen in table V, the population of failures was bimodal, with 7 of 36 specimens failing in less than 1,000 cycles and the remaining specimens reaching the desired runout lives. Preliminary examination of the failed specimens did not reveal anything unusual on the fracture surface, i.e., no large pores or inclusions. Further fracture analysis is planned. In figure 7, the fraction of specimens which failed is plotted as a function of heat treat. As seen in this plot all the low life failures were confined to the J1 and H1 heat treat series. Recall J1 employs a subsolvus, oil quench heat treat while H1 employs a supersolvus, gas fan quench heat treat. Both J1 and H1 also employ a one step age, however, E1 also employs a one step age and did not exhibit the low life failure phenomenon. While the J1 and H1 heat treats are different in certain respects, they both produce microstructures with the best creep resistance and therefore are the most resistant to stress relaxation. This suggests that higher stress levels maintained during the dwell for J1 and H1 may have led to premature failure. Viscoplastic stress analysis of the specimen is being pursued to examine this issue in greater detail. Also, future plans call for continued testing of selected specimens to obtain finite lives beyond the 10,000 cycle runout criteria.

With respect to the spin pit experiment, the E2 heat treat has been selected for several reasons. First and foremost, it did not exhibit the low life failure phenomenon. Second, of the remaining heat treat options it represents a reasonable compromise between strength and crack growth resistance. More detailed testing on the E2 heat treat is planned to fully support the spin pit testing and analysis which is intended to demonstrate high temperature rim capability of LSHR.

Summary and Conclusions

Six potential heat treat options for a 3rd generation PM disk alloy, LSHR, were studied with respect to notch dwell fatigue strength at 1300 °F. Initial results showed two of the six heat treats, J1 and H1, exhibited a bimodal life distribution. The low life population for these two heat treats was less than 1,000 cycles, over one order of magnitude less than the lives of all other specimens tested. These two heat treats were also found to produce the highest creep strength for this alloy. Further work will be required to determine if this factor has contributed to the life deficit for these two heat treatments.

References

1. T.P. Gabb, J. Telesman, P. Kantzos, and K. O'Connor, "Characterization of the Temperature Capability of Advanced Disk Alloy ME3," NASA/TM—2002-211796, August 2002.
2. T.P. Gabb, J. Gayda, J. Telesman, and P. Kantzos, "Thermal and Mechanical Property Characterization of the Advanced Disk Alloy LSHR," NASA/TM—2005-213645, June 2005.
3. S. Jain, "Regional Engine Disk Process Development," NASA Contract NAS3–27720, September 1999.
4. R. Vanstone and T. Richardson, "Potential Drop Monitoring of Cracks in Surface Flaw Specimens," ASTM STP 877, 1985.

TABLE I.—COMPOSITION OF NICKEL-BASE SUPERALLOY LSHR IN WEIGHT PERCENT

Co	Cr	Al	Ti	Mo	W	Nb	Ta	C	B	Zr
21.3	12.9	3.4	3.6	2.7	4.3	1.4	1.7	0.03	0.03	0.05

TABLE II.—HEAT TREATMENTS FOR LSHR

Code	Solution step, °F/hr	Quench	Age	
			°F/4 hr	°F/8 hr
J1	2075	Oil	-----	1425
J2	2075	Oil	1570	1425
E1	2075	Fan air	-----	1425
E2	2075	Fan air	1570	1425
H1	2140	Fan air	-----	1425
H2	2140	Fan air	1570	1425

TABLE III.—1300 °F TENSILE DATA FOR LSHR

Code	Yield, ksi	UTS, ksi	Elongation, percent	RA, percent
J1	170	199	6.5	9.5
J2	169	193	9.0	15
E1	163	191	7.0	11
E2	161	186	9.5	15
H1	155	197	13	16
H2	149	191	19	33

TABLE IV.—CREEP DATA FOR LSHR AT 1300 °F AND 115 KSI

Code	0.2 percent creep, hr	Rupture, hr	Elongation, percent
J1	129	389	6.5
J2	15.7	159	8.9
E1	66.3	322	14.8
E2	9.4	142	13.0
H1	104	378	5.4
H2	17.1	277	6.5

TABLE V.—DWELL NOTCH FATIGUE RESULTS FOR LSHR AT 1300 °F (K_t = 2)

Code	Heat treat	Life (cycles)
J1–N1	Subsolvus/oil/one step age	290
J1–N2	Subsolvus/oil/one step age	10,000+
J1–N3	Subsolvus/oil/one step age	68
J1–N4	Subsolvus/oil/one step age	102
J1–N5	Subsolvus/oil/one step age	2,000+
J1–N6	Subsolvus/oil/one step age	2,000+
J2–N1	Subsolvus/oil/two step age	10,000+
J2–N2	Subsolvus/oil/two step age	10,000+
J2–N3	Subsolvus/oil/two step age	2,000+
J2–N4	Subsolvus/oil/two step age	2,000+
J2–N5	Subsolvus/oil/two step age	2,000+
J2–N6	Subsolvus/oil/two step age	2,000+
E1–N1	Subsolvus/fan/one step age	10,000+
E1–N2	Subsolvus/fan/one step age	10,000+
E1–N3	Subsolvus/fan/one step age	2,000+
E1–N4	Subsolvus/fan/one step age	2,000+
E1–N5	Subsolvus/fan/one step age	2,000+
E1–N6	Subsolvus/fan/one step age	2,000+
E2–N1	Subsolvus/fan/two step age	10,000+
E2–N2	Subsolvus/fan/two step age	10,000+
E2–N3	Subsolvus/fan/two step age	2,000+
E2–N4	Subsolvus/fan/two step age	2,000+
E2–N5	Subsolvus/fan/two step age	2,000+
E2–N6	Subsolvus/fan/two step age	2,000+
H1–N1	Supersolvus/fan/one step age	194
H1–N2	Supersolvus/fan/one step age	368
H1–N3	Supersolvus/fan/one step age	2,000+
H1–N4	Supersolvus/fan/one step age	2,000+
H1–N5	Supersolvus/fan/one step age	663
H1–N6	Supersolvus/fan/one step age	562
H2–N1	Supersolvus/fan/two step age	10,000+
H2–N2	Supersolvus/fan/two step age	10,000+
H2–N3	Supersolvus/fan/two step age	2,000+
H2–N4	Supersolvus/fan/two step age	2,000+
H2–N5	Supersolvus/fan/two step age	2,000+
H2–N6	Supersolvus/fan/two step age	2,000+

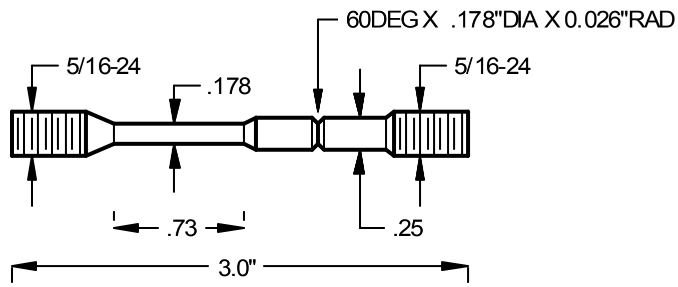

Figure 1.—Design of the creep combo bar. Notch feature of the creep combo bar employs same stress concentration factor as notch fatigue bar ($K_t = 2$).

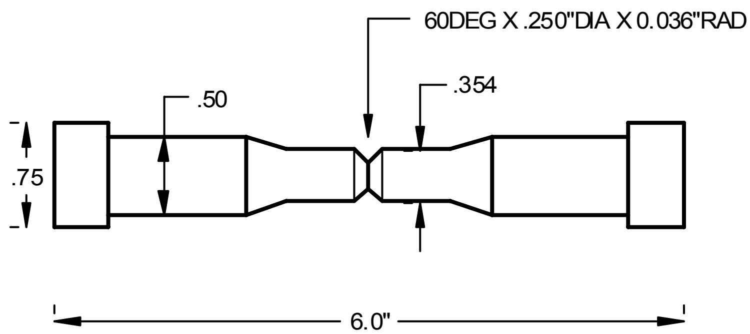

Figure 2.—Design of the notch fatigue specimen ($K_t = 2$). The notch was cut utilizing a low stress grind followed by a longitudinal polish at the base of the notch.

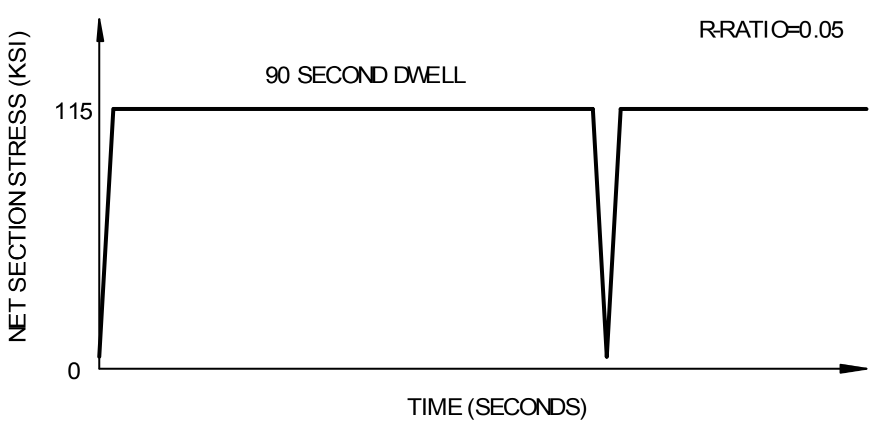

Figure 3.—Waveform of the dwell fatigue cycle employed in this study.

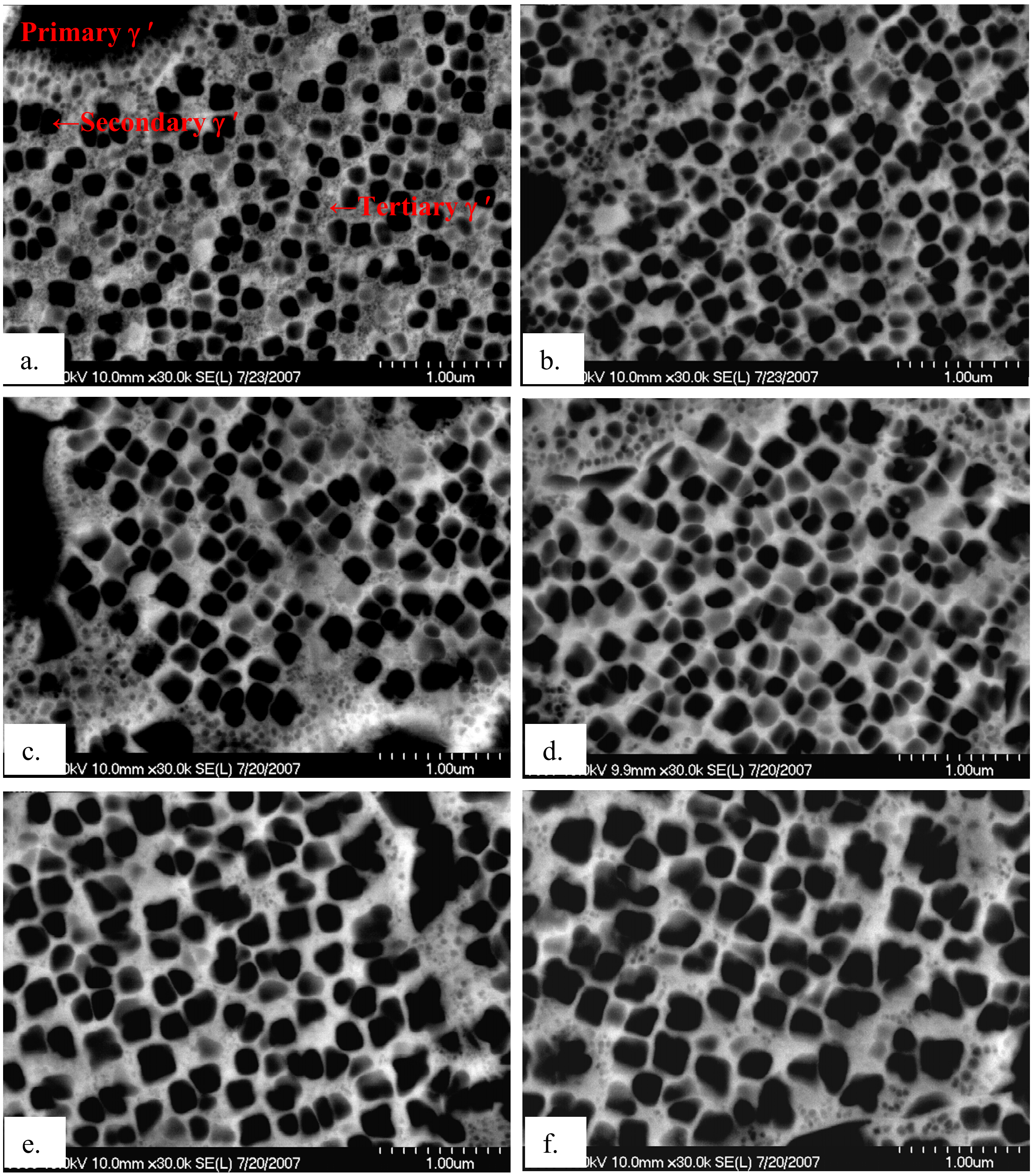

Figure 4.—γ' precipitate microstructures for LSHR after heat treatments: a. J1, b. J2, c. E1, d. E2, e. H1, and f. H2.

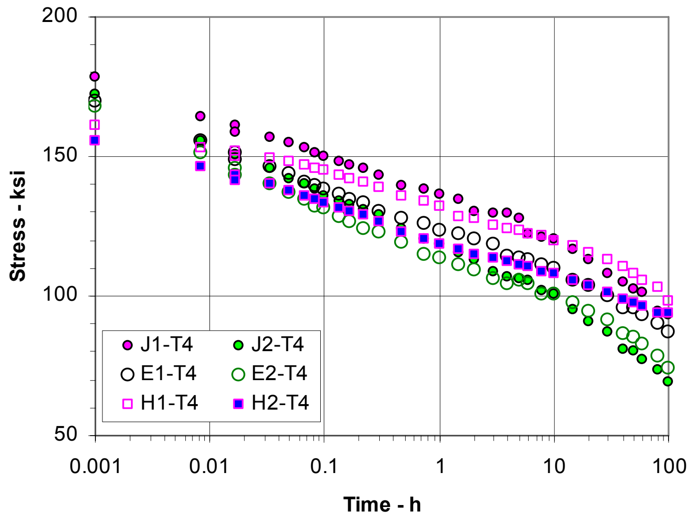

Figure 5.—Stress relaxation data for LSHR as a function of heat treat at 1300 °F. Specimens were loaded to and held at 1 percent strain while monitoring the rate of stress decay.

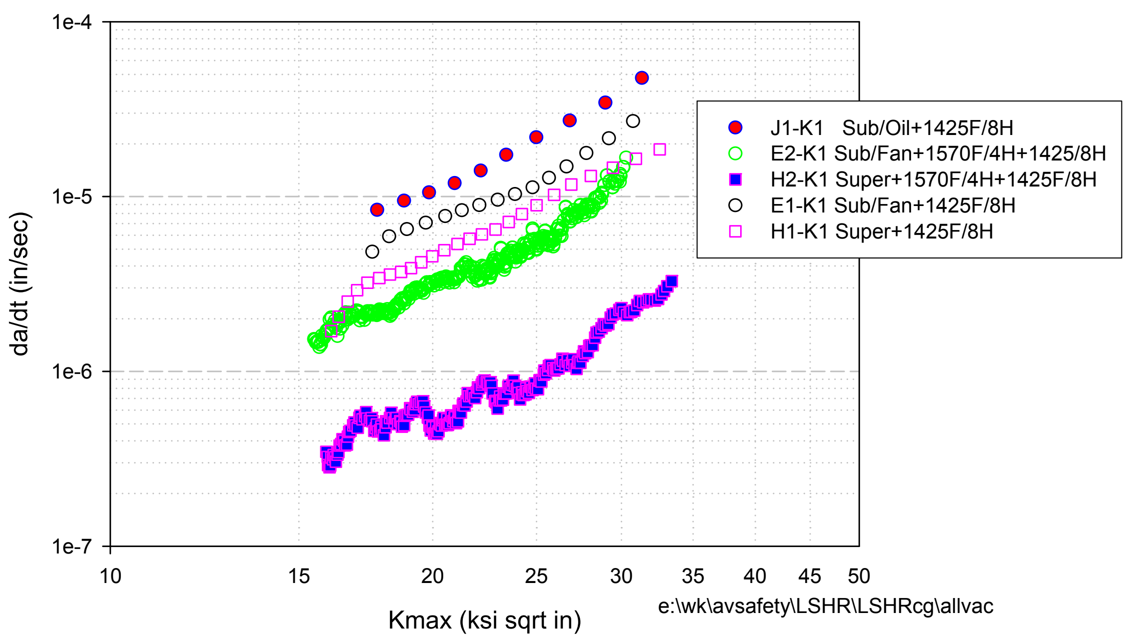

Figure 6.—Dwell crack growth data for LSHR as a function of heat treat at 1300 °F.

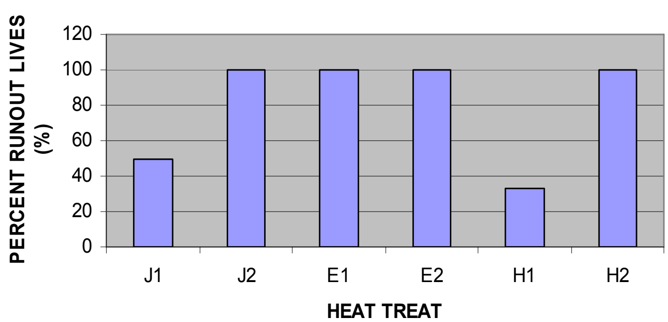

Figure 7.—Notch dwell fatigue data for LSHR at 1300 °F.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
New powder metallurgy (PM) disk superalloys, such as ME3, LSHR, and Alloy 10, have been developed in recent years which enable rim temperatures in turbine disk applications to approach 1300 °F. Before these alloys can be utilized at 1300 °F their long term durability must be ensured. One of the key requirements for disk rims is notch fatigue strength. This issue is extremely important and is a direct result of the blade attachment geometry employed at the disk rim. Further, the imposition of a dwell at maximum load, associated with take off and landing, can also affect notch fatigue strength. For these reasons a study has been undertaken to assess the notch dwell fatigue strength of a modern PM disk alloy through spin pit evaluation of a prototypical disk. The first element of this program involves screening potential heat treatments with respect to notch fatigue strength at 1300 °F utilizing a conventional notch fatigue specimen with a stress concentration factor (K_t) of 2 and a 90 sec dwell at peak load. The results of this effort are reported in this paper including the downselect of an optimal heat treatment, from a notch fatigue standpoint.

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